Seasonal impact on beach morphology and the status of heavy mineral deposition – central Tamil Nadu coast, India

V JOEVIVEK* and N CHANDRASEKAR

Centre for GeoTechnology, Manonmaniam Sundaranar University, Tirunelveli, India.

**Corresponding author. e-mail: vjoevivek@gmail.com*

The aim of the present research was to investigate the seasonal impact on nearshore beach dynamics and the status of heavy mineral distribution along central Tamil Nadu coast, India. Beach profile measurements were made in 10 profiling sites between Thirukadaiyur and Velankanni on monthly and seasonal basis from January 2011 to July 2012. Using beach profile data, variation in beach width, slope and volumetric changes have been calculated. Beach slope and nearshore wave parameters were used to quantify the longshore sediment transport rate. Beaches between Thirukadaiyur and Karaikkal attained predominant transport rate in northern direction whereas, the rest of the beaches are in southern direction. The seasonal action of wind and wave currents create nearshore bar during northeast (NE) monsoon and frequent berms at tidal zone during southwest (SW) monsoon. Surface sediment samples were collected in each location for quantifying the heavy mineral weight percentage during the period of pre- and post-Thane cyclone. Sediments were also studied by X-ray diffraction (XRD) to evaluate the changes and occurrence of heavy minerals in beach sands. The XRD results show that sediments in the study area have enriched heavy mineral distribution even after strong cyclonic event. It confirms the redistribution of heavy mineral deposits present in the coast. The results suggested that monsoonal action has influenced the seasonal changes in beach morphology and it does not affect the heavy mineral distribution.

1. Introduction

Morphological and sedimentological studies have provided valuable information about the nature of beach dynamics and depositional environment. A complete understanding of beach dynamics requires basic knowledge of the coastal configuration. Beach profile study gives the spatio-temporal variation of the foreshore environment. Many researchers, especially, Delgado and Lloyd (2004) have described the simplest methods for measuring beach profiles. Cooper *et al.* (2000) briefly explained the history of beach profile measurement and described the theory and analysis

of beach profiles. Pickett *et al.* (1997) described a model for the analysis of beach profile at Bay of Plenty, New Zealand. In the natural beaches, the assumption of constant wave forcing is not satisfied, as accretion and erosion conditions alternate over time (Quartel *et al.* 2008) and the beach response to wave forcing is not instantaneous (Wright *et al.* 1985). Regional beach profile study has been conducted by Saxena *et al.* (1976), Anil Cherian (2003), Rajamanickam (2006), Antonio and Seelam (2008) and Sheik Mujabar (2010) along southeast coast of India.

Coastal geomorphology not only includes the beach topography but also includes the wave

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process, sediment transport and nearshore dynamics. The wave parameters such as breaker wave height, breaker angle, longshore current velocity and surf zone width play a vital role to control the nearshore processes. The earlier studies (Bijker 1971; Chandramohan *et al.* 1994; Tillotsen and Komar 1997; Sanil Kumar *et al.* 2002) have revealed the importance of wave parameters to examine the sediment transport rate and surf zone dynamics. In the present study, visual and field measurements were made to measure the wave parameters along the central coast of Tamil Nadu (figure 1).

The east coast of India, especially the central Tamil Nadu coast has witnessed several morphodynamic activities. The coastal region experiences three seasonal actions in a year such as NE monsoon (October–January), SW monsoon (June–September), and non-monsoon (February–May). Figure 2 illustrates the seasonal response on wave height, wave period and their direction. The wave rose diagram has been prepared based on standard procedure described in Indian

wave atlas, published by NIO, Goa. The higher wave height is noticed during NE monsoon and waves become calm during non-monsoon season.

According to the Wright and Short morphodynamic state model (Wright and Short 1984), beaches in the present study area have reflective state during the SW monsoon, dissipative state during the NE monsoon and intermediate state during non-monsoon season. Textural and morphodynamic state of the central Tamil Nadu coast is shown in table 1. The sediments present in the study area are mostly unimodal and very well sorted. The mean size of beach sediments ranges from medium-to-very fine sand. Sorting results have shown that samples are very close to the median grain size. The coarse skewed and leptokurtic properties of beach sediments reveal that beach sands are symmetric in structure. Moreover, the beaches are enriched with black sands and heavy minerals (Chandrasekar 1992). Literature studies have shown that major placer deposits such as Garnet, Ilmenite, Rutile,

Figure 1. (a) Location and geomorphology map of the study area and (b) geology map of the study area.

Figure 2. Wave rose diagram describing seasonal changes in wave height and wave period.

Zircon, Monazite and Silliimanite are present in the central Tamil Nadu coast (Chandrasekar 1992; Rajamanickam 1992; Mohan and Rajamanickam 2000; Chandrasekar and Rajamanickam 2002; Rajamanickam and Angusamy 2005; Loveson *et al.*

2008; Suresh Gandhi and Solai 2010; Suresh Gandhi *et al.* 2011). This coast is very sensitive to hydrodynamic processes, sediment supply and beach dynamics. Therefore, an attempt has been made to study the seasonal impact on beach

Table 1. *Textural features and morphodynamic state of the central Tamil Nadu coast.*

Sl. no.	Station	Textural features				Morphodynamic state*
		Mean	Sorting	Skewness	Kurtosis	
1	Tirukadaiyur	2.16	2.18	-0.13	41.21	Dissipative
2	Tharangampadi	2.08	2.05	-0.19	30.25	Intermediate
3	Chandrapadi	2.17	2.13	-0.12	32.53	Dissipative
4	Kottucherryedu	2.29	2.28	-0.09	39.91	Dissipative
5	Kilinjalmadu	2.36	2.24	-0.1	55.49	Intermediate
6	Karaikal	2.69	2.69	-0.03	61.25	Intermediate
7	TR Pattinam	2.14	2.08	-0.06	32.51	Intermediate
8	Nagore	2.16	2.11	-0.08	29.22	Dissipative
9	Nagapattinam	2.51	2.5	-0.01	49.76	Dissipative
10	Velankanni	2.52	2.51	-0.11	56.72	Dissipative

*According to the Wright and Short morphodynamic state model (Wright and Short 1984).

morphology and the status of heavy mineral deposition along the central coast of Tamil Nadu.

2. Area of investigation

2.1 Location

The coastal stretch of the present study area covers a total of 51 km which is located between Thirukadaiyur in the north and Velankanni in the south. It extends between 11°04'N–79°51'E and 10°40'N–79°51'E. The shoreface experiences convergence wave action. Moreover, the area is traversed by complex river channels and coastal construction (harbour, jetties). The study area occupies a major portion of the Cauvery river consisting of narrow wetlands split by various river branches. The Vellar, Pular, Thirumalairajanar, Arasalar, Nallar, Virasolanar are some of the other distributaries, supporting the minor river irrigation system. The location map along with coastal geomorphology is presented in figure 1(a). The geomorphological features were derived from district resource map 1996 with 1:50000 scales, published by GSI.

2.2 Geology

Geological features of the present study area were obtained from GSI published map 1996 with 1:50000 scale and shown in figure 1(b). The eastern part of the study area is covered by alluvium. The age of the outcrops in the study area is from Late Jurassic to Recent. Major Litho units are clay, clay black and alluvium sandy clay. Tharangampadi depression is located to the south of Kumbakonam–Shiyali ridge. It is tracked in the south upto the Karaikkal high and extends into the offshore towards the east. Karaikkal high is a relatively small feature, most of which appears to lie in the offshore. It is aligned nearly ENE–WSW.

2.3 Coastal geomorphology

The study of coastal landforms is one of the fascinating areas of geomorphological research. The coastal tract of central Tamil Nadu consists of an upland plain (denudational), flood plain (fluvial), deltaic plain and coastal plain (marine) (Chandrasekar 1992; Mohan *et al.* 2000). The relief of the north and south Nagapattinam coast is disturbed by estuaries, lagoons and creeks. Beach ridges present along the coast lie almost parallel to the present shoreline. The width of the beach ridges vary from 45 to 150 m. The presence of beach ridges along the coast indicates the shoreline is propagating towards the sea (Revathy *et al.* 2002), since Nagapattinam is located between two big beach ridge systems, largely affected by heavy rainfall and storm surge during the NE monsoon. A series of sand dunes occur parallel to the coast around TR Pattinam, Karaikkal, Kottucherryedu, Kilinjalmadu and Chandrapadi. Dunes are located very close to the beaches with a height of 8 m. Vegetation and settlements are present in the dunes in a stabilized condition. The beach sediments are mainly composed of quartz, feldspar along with heavy minerals (Chandrasekar 1992).

3. Materials and methods

3.1 Beach profile survey

The beach profile survey was carried out on monthly and seasonal basis from January 2011 to July 2012. Totally, 10 stations with an approximate interval of 5 km were fixed between Thirukadaiyur and Velankanni. Depending upon the river confluence, delta mouth and swamp, the profiling sites have been varied but do not exceed 4 km. The slope of each profile segment is measured using total station (Trimble® M3). In each station, slope is measured at 2-m interval from

Figure 3. (a-j) Seasonal variation in beach profiles along the study area.

Table 2. *Seasonal basis beach width variation along the study area.*

Station	Beach width (m)						
	Jan-11	Apr-11	Jul-11	Oct-11	Jan-12	Apr-12	Jul-12
Thirukadaiyur	83	89	79	80	69	76	78
Tharangampadi	18	20	26	40	18	20	26
Chandrapadi	63	59	64	64	53	60	62
Kottucherry medu	66	64	63	65	54	61	63
Kilinjalemedu	61	56	58	61	49	59	58
Karaikkal	187	181	178	187	171	176	178
TR Pattinam	89	88	90	91	78	84	88
Nagore	91	88	86	89	81	88	90
Nagapattinam	96	83	88	87	73	81	86
Velankanni	74	76	68	72	67	71	73

Table 3. *Seasonal basis beach slope variation along the study area.*

Station	Nearshore beach slope (in rad)						
	Jan-11	Apr-11	Jul-11	Oct-11	Jan-12	Apr-12	Jul-12
Thirukadaiyur	0.1084	0.1502	0.1641	0.1447	0.1002	0.107	0.1052
Tharangampadi	0.1043	0.1405	0.0961	0.1014	0.1052	0.1303	0.1607
Chandrapadi	0.1514	0.2116	0.1352	0.2008	0.1607	0.1394	0.1304
Kottucherry medu	0.1386	0.1354	0.1407	0.1743	0.1102	0.1622	0.2424
Kilinjale medu	0.159	0.1506	0.1463	0.1462	0.1506	0.1776	0.1912
Karaikkal	0.111	0.1563	0.1416	0.1886	0.1103	0.1564	0.2269
TR Pattinam	0.127	0.1304	0.121	0.147	0.1202	0.1138	0.1455
Nagore	0.1217	0.1607	0.1464	0.1106	0.1253	0.1447	0.181
Nagapattinam	0.131	0.1102	0.1715	0.1228	0.1658	0.17	0.1708
Velankanni	0.1015	0.1556	0.1367	0.0975	0.1102	0.1011	0.0851

backshore to foreshore region. The measured data are adjusted to the bench mark of the area in the survey of India toposheet and the mean sea level is based on the chart datum (chart no. 3007, scale 1:35,000, year 2010) published by NHO, Dehradun. A simple visual basic model BEACH developed by Chandrasekar and Sheik Mujabar (2010) has been utilized for beach profile analysis.

3.2 Measuring nearshore parameters

The nearshore wave parameters were measured during the same period along the ten profile sites. The breaker wave height (H_b) was measured using a calibrated staff. Two persons measured crest and trough of the breaker waves and significant wave height was obtained by averaging the recorded wave height of twenty successive waves. The direction of breaker locator was fixed visually using GPS and the digital compass. At the breaker locator, base of the rope was tied with boat edge and other side set to free floating. The breaker angle was measured by length of deviation in the rope observed by total station. The longshore current

velocity measured by the buoyant plate travelled the distance in 2 min beyond the surf zone. The surf zone width was measured as the distance between boat and total station.

3.3 Heavy mineral separation

Surface sediment samples were collected in each profile site during the same period seasonally. Three samples were collected at each site from low tide, high tide and berm region which are not affected by plastic and other debris. The dried sediment samples were pre-treated to remove the clay, organic and shelly materials. The treated samples were sieved by mechanical sieve shaker in a $1/4 \phi$ interval (ranging from 1.25 to 4ϕ). The textural features (mean, standard deviation, skewness and kurtosis) of sieved data were computed based on standard statistical procedure (Folk and Ward 1957). Heavy and light minerals in the respective fractions were separated by bromoform (specific gravity 2.89 and molecular weight 252.73 g/mol) as per the standard procedure suggested by Milner (1962).

Table 4. Seasonal basis beach sediment volume along the study area.

Station	Beach sediment volume (m ³)						
	Jan-11	Apr-11	Jul-11	Oct-11	Jan-12	Apr-12	Jul-12
Thirukadaiyur	52.49	58.26	58.72	57.9	54.66	54.22	58.54
Tharangampadi	6.92	7.39	8.33	13.29	5.12	5.21	7.37
Chandrapadi	27.75	35.13	44.74	39.55	20.89	34.95	44.62
Kottucherrymedu	15.30	28.46	38.81	41.93	21.35	34.19	40.55
Kilinjalmadu	43.98	38.30	41.16	35.92	37.25	36.48	40.44
Karaikkal	59.38	83.94	74.12	71.34	72.26	86.06	70.02
TR Pattinam	62.24	64.51	67.39	75.09	69.71	71.75	65.31
Nagore	52.74	76.63	62.33	59.73	45.79	75.25	62.02
Nagapattinam	67.06	37.08	76.84	74.06	28.29	36.87	76
Velankanni	48.41	41.66	47.15	28.16	32.04	36.15	46.18

4. Results

4.1 Beach morphology

The data obtained from January 2011 to July 2012 yield an extensive dataset that could be used to determine the seasonal impact on beach morphology (figure 3). The cross-shore beach profile has shown that ridge and runnel systems are present in the coast during the period between NE and non-monsoon. The ridge and runnel pattern is formed in the foreshore region due to interaction of waves, tides, currents and beach topography. However, the runnels become almost flat due to sand accumulation by strong onshore winds during the rest of the period.

The process of seasonal wave action is shifting the sand materials from berm to bar and back again (Bascom 1951). The variation in the berm and beach slope indicates that excess of wave energy emanated during NE monsoon removing the material from the berm crest and carrying it towards the sea. During the cyclone surge, seaward flowing bottom currents remove the lesser sediments from the beach face and move it towards the sea. At the same time, surging waves create a series of abandoned berms at the backshore region (figure 3i). The lower wave energy during SW and non-monsoon seasons remove the lesser amount of sediments at the bottom of the beach in backrush and drop some sand during uprush thus resulting in deposition. During the period of storm surge, the beaches attain a flat terrace at low tide region (figure 3). This is due to wave backrush, which removes the foreshore sediments and drops it in nearshore region forming a surf zone bar.

The relation between beachface slope and sediment size variation is well established by Bascom (1951). Sharp crest and flat berm top at Karaikkal beach have confirmed that moderate grain size (ranging between 1.25 and 2.50 ϕ) are present in the beach. Beachface slope from Nagore to Velankanni correspond to wave height

ranging from 1.0–1.25 m, implying that fine grained sediments with dissipative state prevailed in the coast. The presence of medium-to-very fine sands in the beach indicates that beachface slope attains equilibrium condition through onshore/offshore sediment transport (Heitor and Cristina 2010). The bi-model nature of grain size distribution along the beach profile clearly indicates the gradual shift in sediment volume and heavy mineral percentage.

4.1.1 Beach width

Beach width variation in SW to NE monsoon (table 2) indicates that beaches of Nagapattinam, TR Pattinam, Karaikkal, Kottucherryedu, Chandrapadi, Tharangampadi are eroding considerably whereas, the beaches of Velankanni, Nagore, Kilinjalmadu and Thirukadaiyur show accretion trend. Within a short period of time (September 2011–December 2011), Tharangampadi beach attains significant variation due to presence of coastal structures (man-made constructions) that obstruct the movement of littoral sand. The sediments are transported by uprush that creates numerous berms at backshore region. These sediment deposits form a beach ridge due to repeated aeolian process by wave currents. Beach width for July 2011 and July 2012 reflect the sediment rework by seasonal act and continuous wave action.

4.1.2 Beach slope

The profile variation of beach topography revealed that steep slope is associated with accretion and flat slope is associated with erosion. The beach slope is presented in radian units (table 3). During the period between SW and NE monsoon, the slope face is decreased considerably. This is due to seasonal changes in wave action transporting the sediments from berm to nearshore and formation of a longshore bar. The slope of Karaikkal beach clearly reflects the bar-berm variation during monsoon periods. The maximum steep slope is observed at Karaikkal beach (0.1886 rad) during

Table 5. *Seasonal variation on breaker wave height, longshore current and surf zone width.*

Station	Jan-11	Apr-11	Jul-11	Oct-11	Jan-12	Apr-12	Jul-12
Breaker wave height (H_b)(m)							
Thirukadaiyur	0.88	0.68	0.58	0.56	0.97	0.73	0.51
Tharangampadi	0.82	0.72	0.54	0.64	0.95	0.76	0.47
Chandrapadi	0.74	0.94	0.57	0.66	0.96	0.73	0.5
Kottucherrymedu	0.94	0.74	0.55	0.76	1.02	0.85	0.42
Kilinjalmadu	0.88	0.78	0.53	0.66	1.04	0.84	0.46
Karaikkal	0.83	0.68	0.66	0.65	0.98	0.82	0.78
TR Pattinam	0.92	0.75	0.46	0.61	0.94	0.73	0.39
Nagore	0.92	0.74	0.68	0.74	0.96	0.79	0.61
Nagapattinam	0.98	0.86	0.59	0.61	1.03	0.75	0.52
Velankanni	0.7	0.67	0.6	0.62	0.96	0.76	0.53
Longshore current velocity (V)(m/s)							
Thirukadaiyur	0.111	-0.167	-0.150	-0.182	0.27	-0.09	-0.16
Tharangampadi	0.216	-0.161	-0.133	-0.229	0.23	-0.19	-0.13
Chandrapadi	0.163	-0.166	-0.120	-0.190	0.25	-0.25	-0.11
Kottucherrymedu	0.168	-0.150	-0.139	-0.123	0.27	-0.24	-0.14
Kilinjalmadu	0.177	-0.183	-0.120	-0.214	0.28	-0.24	-0.15
Karaikkal	0.099	-0.139	-0.149	-0.261	0.39	-0.20	-0.13
TR Pattinam	0.172	-0.161	-0.143	-0.161	0.39	-0.15	-0.12
Nagore	0.214	-0.175	-0.134	-0.176	0.25	-0.24	-0.14
Nagapattinam	0.301	-0.238	-0.114	-0.189	0.33	-0.22	-0.15
Velankanni	0.239	-0.128	-0.114	-0.140	0.28	-0.20	-0.12
Surf zone width (m)							
Thirukadaiyur	57	31	29	37	64	42	18
Tharangampadi	64	35	48	58	67	38	24
Chandrapadi	40	21	28	30	44	32	34
Kottucherrymedu	43	38	35	33	66	34	31
Kilinjalmadu	39	35	28	41	49	30	25
Karaikkal	60	33	31	32	65	32	25
TR Pattinam	50	40	32	39	58	39	34
Nagore	49	31	27	55	54	34	28
Nagapattinam	46	44	24	46	41	32	25
Velankanni	58	29	33	59	58	48	28

Note: (-) sign indicates northern direction and (+) sign indicates southern direction.

the SW monsoon and gentle slope is recorded at Velankanni (0.0851 rad) for all the seasons. It is evident that the southern part of the central Tamil Nadu coast has low energy wave action.

4.1.3 Beach sand volume

The sediment volume along the different beaches undergoes typical seasonal changes due to hydrodynamic conditions. Sand volume is increased in the SW monsoon period and decreased in NE monsoon period (table 4). Among the beaches, Nagapattinam exhibits more volumetric changes in NE monsoon due to Thane cyclone. During this period, sediments are transported into foreshore, resulting in abundant longshore bars being formed at nearshore. The post-storm process creates creek formation at Nagapattinam due to low

lands present in the area. Thereby the coast is prone to risk from storm surge flooding. On these beaches rhythmic bar-beach morphology is observed which indicates nearshore circulation during calm days. It is possible that many strong currents are present to recycle the sediments and favour the deposition of heavy minerals.

4.2 Nearshore processes

Nearshore measurement is an important phase of coastal monitoring that delivers the wave environment of the coastal zone. Wave parameters, particularly, breaker wave height, breaker angle, longshore current velocity and surf zone width have strong convergence force to direct the nearshore processes. Methods used to quantify nearshore wave parameters are described earlier in the methodology section. The results

Figure 4. Wave refraction diagram (Bathymetric contours are in metre). (a) 6 sec wave period during NE monsoon, (b) 8 sec wave period during NE monsoon, (c) 8 sec wave period during SW monsoon, (d) 10 sec wave period during SW monsoon (stations – TKR: Thirukadaiyur, KRL: Karaikkal, NGP: Nagapattinam, VKN: Velankanni) (after Chandrasekar 1992).

were interpreted based on Longuet-Higgins (1970) and Galvin (1963), Shoreline protection manual (1984) and Coastal Engineering Manual (2002). Table 5 illustrates the maximum wave height (1.25 m) recorded at Karaikkal beach and minimum (0.63 m) at Velankanni. The prolong period of wide range of wave heights during summer is prone to the development of strong rip currents and replenishes the sediments to the beaches. The coast produces surging breakers more during NE monsoon than during the rest of the period.

The breaker angle is projected towards the south during NE monsoon whereas it is shifted towards the north for the rest of the period. The longshore current propagates towards north between March and October 2011. The maximum magnitude of longshore current (0.41 m/s) towards south is observed at Karaikkal and Nagapattinam during January 2012. It implies that higher sediment transport takes place during NE monsoon. The surf zone width varies between 31 and 91 m. The surf zone width increases during NE monsoon due to the presence of longshore bar at nearshore region.

Nearshore waves approach the coast predominantly in NE and SW directions. Wave period mostly prevails for about 6–8 sec during the NE monsoon and 8–10 sec during the rest of the period. Littoral currents are moderate to strong during SW monsoon and variable during NE monsoon. Chauhan (1995) inferred that NE and SW monsoon controls the longshore sediment

transport along the east coast of India. Hence, wave refraction pattern have been drawn for NE (45°) and SW (135°) monsoon with different wave periods. Figure 4 shows a quantitative picture of littoral currents prevailing in the east. It reflects the dominance of the low energy environment. However, the zone of convergence favours the deposition of heavy mineral placer along the beaches. During NE monsoon, the coast expresses sporadic enhancements in the wind and wave climate due to occurrence of the cyclone/storm. The littoral current direction together with the submerged ridges has also been confirmed by orientation in arrow symbol (figure 4). It indicates that submerged ridges play a vital role in the process of beach morphology along the present study area.

4.3 Longshore sediment transport

The littoral zone is the most dynamic environment along the coast where constant mobility of sediment is observed. The phenomenon of longshore sediment transport plays a vital role in the studies related to beach erosion, shoreline migration, harbour design and sedimentation, etc. Many researchers especially, King (1972, 1974), Willis (1980), Shore Protection Manual (1984), Walton and Bruno (1989), Chandrasekar (1992) and Anil Cherian (2003) have developed and used empirical relation to estimate longshore sediment transport.

Table 6. *Estimated longshore sediment transport rate (Q).*

Period	Estimated longshore sediment transport rate (in $1000 \text{ m}^3/\text{month}$) based on measured wave data									
	Kottucherry-					TR				
	Thirukadaiyur	Tharangampadi	Chandrapadi	medu	Kilinjai-	Karaikal	Pattinam	Nagore	Nagapattinam	Velankanni
Jan-11	294.7261	600.0476	255.398	359.4543	321.5575	260.9772	418.8171	510.6646	718.2713	513.6438
Feb-11	213.4316	346.3181	220.6137	314.9894	275.5617	169.0778	347.9697	223.7029	193.3747	242.0797
Mar-11	-205.657	-195.661	-149.593	-253.183	-221.678	-250.477	-292.944	-137.546	-248.807	-260.49
Apr-11	-186.348	-214.766	-173.458	-223.277	-264.455	-165.111	-255.673	-212.505	-476.723	-131.65
May-11	-297.703	-336.485	-153.671	-222.22	-213.432	-307.059	-324.12	-361.69	-308.968	-257.822
Jun-11	-234.461	-264.674	-256.551	-224.609	-197.085	-238.443	-152.095	-180.159	-139.264	-206.595
Jul-11	-133.554	-182.484	-101.38	-141.639	-94.2656	-161.373	-111.425	-130.231	-85.4488	-119.484
Aug-11	-120.532	-228.357	-55.759	-99.6014	-73.4391	-143.982	-88.2247	-98.9694	-113.719	-125.645
Sep-11	-121.656	-177.898	-28.0129	-116.587	-61.1615	-149.741	-81.0638	-92.9761	-100.746	-114.834
Oct-11	-199.618	-449.968	-199.139	-163.294	-306.535	-287.37	-202.749	-379.18	-280.729	-271.088
Nov-11	334.7128	345.4606	175.0139	287.2878	355.6208	268.9492	281.2405	410.1475	378.2333	368.7792
Dec-11	405.1812	556.3665	339.8898	402.1302	405.0253	959.9381	492.2011	569.9728	661.1292	544.2284
Jan-12	558.6486	572.7768	424.8304	506.0234	469.3716	724.9633	519.4772	576.2652	312.9588	442.1082
Apr-12	-304.631	-289.544	-312.105	-368.836	-319.614	-273.216	-227.413	-338.535	-276.191	-380.609
Jul-12	-77.7501	-77.623	-98.9874	-96.4888	-91.3119	-134.189	-84.2292	-126.577	-103.222	-94.2656
Annual longshore sediment transport rate (in $1000 \text{ m}^3/\text{year}$)										
Northerly	-1499.53	-2050.29	-1117.56	-1444.41	-1432.05	-1703.56	-1508.29	-1593.26	-1754.4	-1487.61
Southerly	1248.052	1848.193	990.9153	1363.862	1357.765	1658.942	1540.228	1714.488	1951.009	1668.731
Annual net transport	-251.477	-202.1	-126.648	-80.5496	-74.2857	-44.6131	31.93374	121.2308	196.6038	181.1232
Annual gross transport	2747.58	3898.486	2108.479	2808.273	2789.816	3362.498	3048.523	3307.745	3705.413	3156.339

Note: (−) sign indicates northern direction and (+) sign indicates southern direction.

Figure 5. (a) Sediment accumulation during reflective morphodynamic state (October 2011) and erosion during dissipative morphodynamic state (January 2012). The circles are common landmark that indicates significant changes in deposition and erosion (station: Tharangampadi), (b) heavy mineral patches and lamination, (c) ripple formation of heavy mineral enriched beach sands and (d) thick lamination of heavy mineral deposition in river mouth (Kottucherryedu).

Table 7. Heavy mineral weight percentage in surface sediments along the study area.

Sl. no.	Stations	December 2011			January 2012		
		LT	HT	Berm	LT	HT	Berm
1	Thirukadaiyur	11.74	61.23	59.37	13.74	56.51	63.12
2	Tharangampadi	3.42	36.19	23.34	1.6	32.94	16.6
3	Chandrapadi	2.85	56.24	68.91	3.22	60.52	73.48
4	Kottucherry medu	1.86	54.35	66.54	0.24	58.74	71.84
5	Kilinjalmadu	18.58	66.41	75.19	23.72	64.02	79.92
6	Karaikkal	6.23	73.95	84.65	5.7	77.96	83.62
7	TR Pattinam	8.98	62.17	56.32	10.28	61.54	54.38
8	Nagore	1.2	57.32	52.12	0.4	55.78	46.38
9	Nagapattinam	4.61	53.19	70.84	6.44	49	72.88
10	Velankanni	9.45	41.23	51.18	11.02	36.86	48.16

Walton and Bruno (1989) equation provides simple and generalized way to determine the longshore sediment transport.

$$Q = \frac{1290 \times P \times g \times H_b \times W \times V \times C_f}{0.78 \times (5\pi/2) \times (V/V_0)},$$

where Q is the longshore sediment transport rate (m^3/year), P is the mass density of the sea water (1025 kg/m^3), g is the acceleration due to gravity (9.8 m/s^2), C_f is the friction co-efficient (≈ 0.01), H_b and W are the breaking wave height (m) and surf zone width (m), respectively. V is the measured longshore current velocity (m/s), V/V_0 is the theoretical dimensionless longshore current velocity (≈ 0.4 according to Longuet-Higgins 1970).

The estimated longshore transport rate of the entire coast is presented in table 6. Sediment transport is northerly during April to October and southerly during November to March in the entire stretch. The sediment transport rate is relatively high exceeding $2 \times 10^5 \text{ m}^3/\text{month}$ during the northeast monsoon period (November–January) and relatively low about $0.1 \times 10^5 \text{ m}^3/\text{month}$ between March and October 2011. This represents the dynamic portion of the beach system due to wave forcing. This has been exhibited in the beach face profile. In Tharangampadi, submerged structures in the offshore is posing the greatest threats to sediment circulation and rip currents are prominent and reflected by the presence of crescentic bars, transverse bars and cusped beaches. Therefore, the beach is highly deposited in October 2011 and largely eroded in January 2012 (figure 5a).

4.4 Heavy mineral distribution

Beach sands containing heavy mineral placers are found along the shoreline in the form of dissemination, patches and lamination (figure 5b). The beaches between Nagapattinam and Karaikkal have a symmetrical or asymmetrical ripple formation, and heavy mineral concentration is noticed in the troughs (figure 5c). During the non-monsoon season, a thick alluvial lamination

can be seen in the river mouth (figure 5d). Heavy mineral weight percentage of surface sediment samples during December 2011–January 2012 is given in table 7. Surface heavy mineral weight percentage in the low tide is comparatively lower than high-tide and berm region. During the NE monsoon, wave backrush drops the heavy minerals resulting in heavy mineral patches settled at high-tide (HT) and mid-tide (MT) region. There is no significant change noticed in heavy mineral concentration during the period of pre- and post-Thane cyclone.

4.4.1 XRD study

Heavy mineral phases in sediment samples were identified using single crystal XRD instrument (Model no. PW3050/60). The samples were scanned continuously for 10 – 80° with a step size of 0.0170 (2θ). Measurement temperature was fixed at 25°C and Copper was used as an anode material. JCPDS-ICDD 2003 database cards were used to identify different heavy minerals present in the sediment samples. Peaks for different heavy minerals and their card numbers are as follows: Magnetite, d: 2.965, 2.097 and 1.614, JCPDS card no. 80-0390; Ilmenite, d: 2.730, 1.860 and 1.720, card no. 03-0789; Garnet, d: 2.920, 2.610, 1.560 and 1.270, card no. 02-0981; Rutile, d: 3.240, 1.683 and 1.091, card no. 78-1510; Zircon, d: 3.324, 2.541 and 1.725, card no. 81-0591. XRD plot of Nagapattinam beach sediments for the period of December 2011 and January 2012 is shown in figure 6. In both the plots, zircon peaks are much intensified. The peaks have shown that the occurrence of heavy minerals does not change but, their peak intensities are varied. It shows the stability of heavy mineral deposits even the beaches are affected by heavy storms.

5. Discussion

The NE and SW monsoons are the predominant cause of beach morphological changes. The higher

Figure 6. XRD peaks of Nagapattinam beach sediments on (a) December 2011 and (b) January 2012.

portion of waves comes from the N and NE during NE monsoon producing the reversed longshore currents towards south. During this period, wave backrush carries the sediments in seaward direction, forming longshore bars at nearshore region. The coast between TR Pattinam and Velankanni has attained predominant transport rate in southern direction. The rest of the beaches have attained predominant transport rate in northern direction.

The presence of beach ridges along the coastline indicates that the present shoreline is prograding towards the sea. The continuous sediment supply by minor river system and the surf zone wave action have created an enrichment of placer deposits in the beaches between Thirukadaiyur and Velankanni. The Ilmenite dominated black sands broadly distributed in the study area can be seen by the naked eye. Although the heavy mineral concentration is found in shoreface regions, they have attained non-uniform distribution. Garnet dominates northern part of the Tharangampadi whereas, thick concentration of Ilmenite grains can be seen between Karaikkal and Nagapattinam. This is due to density sorting during sediment transport process and winnowing action of waves and currents. The Zircon deposits are primarily seen on the coast between Tharangampadi and Karaikkal. The weight percentage of heavy minerals in tidal and berm regions is evident for the redistribution of heavies even after Thane cyclone.

The wave refraction pattern for 8 and 10 s indicates a strong convergence wave action along the study area. But it has supplemented the low-energy environment prevailing in the region where the heavy mineral deposition is also found to be active (Chandrasekar 1992). This is being mainly controlled by coastal configuration and geomorphology of the region (Rao *et al.* 2001).

The entire study area has been affected by the recent tropical cyclone Thane during 25th and 30th December 2011. The response of Thane storm surge results in removal of sediments from the berm and forming it longshore bar at backshore. After the Thane surge, field investigations were made and it was found that there are no significant changes in the black sand distribution. Further, Karaikkal and Nagapattinam beaches have developed a series of berms at backshore region due to storm surge as well as cyclonic wind effect.

6. Conclusion

The results of this investigation reveal that the erosion and accretion events are derived by wave currents and monsoonal climate action. During the study period, it can be seen that NE monsoon created intense wave climate and storm

with heavy rainfall that resulted in heavy damages in the coastal region. The beaches between Thirukadaiyur and Karaikkal have a predominant transport rate in northern direction and the rest of the beaches accomplish the same in southern direction. Thereby the beach profile indicates the strong seasonal variability in erosion at NE monsoon and accretion at SW and non-monsoon seasons. The winnowing effect of wave currents generates beach ridges and inland sediment deposits all along the coast. Nearshore wave climate displays significant changes in February and October months. The storm surge acts as a physical force to create inland deposition and sand bar formation near surf zone. River mouth/estuary appear to influence both the magnitude and characteristics of waves reworking the beach sediments. Heavy mineral weight percentage in December 2011 and January 2012 shows the intense distribution in berm region. X-ray diffraction study revealed that the heavy mineral distribution remains approximately the same even after Thane cyclone. Overall, it is concluded that seasonal action can induce the changes on beach morphology but does not affect the heavy mineral distribution.

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